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**PATENT APPLICATION  
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**OPTICAL APPARATUS, COMPRISING A BRIGHTNESS CONVERTER, FOR  
PROVIDING OPTICAL RADIATION**

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1       **OPTICAL APPARATUS, COMPRISING A BRIGHTNESS CONVERTER, FOR**  
2                                   **PROVIDING OPTICAL RADIATION**

3  
4                   **Cross Reference to Related Applications**

5           The present application is a U.S. National Stage filing of Patent Cooperation  
6 Treaty ("PCT") application serial number PCT/GB2004/002535, filed 11 June 2004,  
7 which in turn claims priority to United Kingdom (Great Britain) Patent Application  
8 Serial Number GB0313592.8, filed 12 June 2003, and United Kingdom (Great  
9 Britain) Patent Application Serial Number GB0323663.5, filed 9 October 2003.

10  
11                   **Field of Invention**

12           This invention relates to an apparatus for providing optical radiation. The  
13 invention can take various forms, for example a laser, a Q-switched fibre laser, a  
14 master oscillator power amplifier, or a laser that contains a frequency converter. The  
15 invention has application for materials processing.

16  
17                   **Background to the Invention**

18           Pulsed Neodymium doped Yttrium Aluminium Garnet (Nd:YAG) lasers are  
19 widely used in industrial processes such as welding, cutting and marking. Care has  
20 to be taken in these processes to ensure that the plasmas generated by the laser  
21 does not interfere with the incoming laser pulses. The relatively low pulse repetition  
22 rates (6kHz) at high peak powers that are achievable in a NdYAG laser have led to  
23 their wide application in laser machining. The most common format for Nd:YAG  
24 lasers are so-called rod lasers in which the Nd:YAG is formed in a rod and is  
25 pumped either by lamps or by laser diodes. A disadvantage of rod lasers is the  
26 degradation of beam quality as the output power is increased. This is because of  
27 "thermal lensing" within the Nd:YAG crystal. Thermal lensing becomes important for  
28 output powers in excess of 500W. The beam quality can be defined in terms of the  
29 beam parameter product, which is the beam radius in mm at the beam waist  
30 multiplied by the (half-angle) divergence angle in mrad. Typical values for beam  
31 parameter products are 25mm.mrad for a 6kW lamp-pumped Nd:YAG laser, and  
32 12.5mm.mrad for a 6kW diode-pumped Nd:YAG laser. Lasers having such power  
33 levels and beam parameters are widely used in welding applications.

1 Much work has been undertaken to improve high-power laser performance in  
2 terms of beam parameter and reliability. Ytterbium doped Yttrium Aluminium Garnet  
3 (Yb:YAG) is one of the most promising laser-active materials and more suitable for  
4 diode-pumping than the traditional Nd-doped crystals. It can be pumped at 0.94  $\mu\text{m}$   
5 and generates 1.03  $\mu\text{m}$  laser output. Compared with the commonly used Nd:YAG  
6 crystal, Yb:YAG crystal has a larger absorption bandwidth in order to reduce thermal  
7 management requirements for diode lasers, a longer upper-state lifetime, three to  
8 four times lower thermal loading per unit pump power. Yb:YAG crystal is expected to  
9 replace Nd:YAG crystal for high power diode-pumped lasers and other potential  
10 applications.

11 Changing from rods to disks has been demonstrated to provide a route  
12 towards increasing the beam quality. Disk lasers containing several Yb:YAG disks of  
13 several mm thickness can be designed to have a beam parameter product of around  
14 8mm.rad thus making the lasers suitable for both welding and some cutting  
15 applications. The disks have a diameter of 5 to 10mm in order to facilitate efficient  
16 coupling from laser diodes. A disadvantage of the disk laser is that a long optical  
17 path needs to be provided external to the disks in order to achieve the required  
18 beam quality. Provision of such a long optical path results in a laser that is difficult to  
19 design and make, and also a laser that is susceptible to environmental disturbance,  
20 such as temperature changes and vibration.

21 Fibre lasers are increasingly being used for materials processing applications  
22 such as welding, cutting and marking. Their advantages include high efficiency,  
23 robustness and high beam quality. These advantages arise because the laser cavity  
24 is formed in a waveguide. Examples include femtosecond lasers for multiphoton  
25 processing such as the imaging of biological tissues, Q-switched lasers for  
26 machining applications, and high-power continuous-wave lasers. In many  
27 applications, fibre lasers need to compete with the more mature diode pumped solid  
28 state lasers. In order to do so, much greater optical powers need to be achieved,  
29 with high reliability and lower cost.

30 Fibre lasers are typically longer than diode-pumped solid state lasers, and this  
31 leads to non-linear limitations such as Raman scattering becoming problematical. It  
32 would be advantageous to have fibre lasers that are shorter.

1 Fibre lasers are typically pumped with diode lasers in bar or stack form. The  
2 output from bars and stacks is not ideally matched to the geometry of fibre lasers,  
3 leading to a loss in brightness. The loss in brightness results in the need to supply  
4 the pump radiation into the cladding of the fibre laser, and this increases the length  
5 of cladding pumped fibre lasers in order to obtain the necessary absorption and  
6 output energy. High power fibre lasers can be 5m to 10m long, and are typically  
7 formed in fibres having diameters in the range 100 $\mu$ m to 500 $\mu$ m.

8 An aim of the present invention is to provide apparatus for providing optical  
9 radiation that reduces the above aforementioned problems.

### 11 **Summary of the Invention**

12 According to a non-limiting embodiment of the present invention, there is  
13 provided apparatus for providing optical radiation, which apparatus comprises a  
14 pump source for providing pump radiation, and a brightness converter, the apparatus  
15 being characterised in that the brightness converter contains a substantially rigid  
16 region along at least a portion of its length.

17 An advantage in providing a brightness converter that is substantially rigid  
18 along at least a portion of its length is that good beam quality (a beam parameter  
19 product less than 12.5mm.mrad, combined with high power (greater than 500W, and  
20 preferably greater than 5kW) can be achieved in a solid state laser having relatively  
21 stiff member. It also provides a route to achieving beam parameter products less  
22 than 8mm.mrad, and preferably less than 5mm.mrad.

23 The invention is counter-intuitive in that it is the complete opposite solution that  
24 has been provided to date with fibre lasers in which the optical fibre used to form the  
25 fibre laser is in the form of a fibre. The optical fibre of prior art fibre lasers is flexible.

26 One aspect of the present invention is to replace the Nd:YAG or Yb:YAG rod  
27 with a relatively thick (>1mm, and preferably greater than 2mm in at least one cross-  
28 sectional dimension) optical fibre waveguide having a core and a cladding. The  
29 resulting design can provide output power levels at levels comparable to diode-  
30 pumped Nd:YAG lasers with the beam quality of the disk laser, and this without the  
31 environmental sensitivity of the disk laser. In other words, fibre optic technology can  
32 solve the thermal lensing problem that occurs in rod lasers and this has advantages  
33 over replacing the rod with a disk made of the same or similar material.

1 The brightness converter may comprise a core, a first cladding, rare earth  
2 dopant, a first end, and a second end. The brightness converter may comprise a  
3 tapered region located between the first end and the second end, the apparatus  
4 being characterised in that the cross-sectional area of the first end is greater than the  
5 cross-sectional area of the second end, and the brightness converter is substantially  
6 rigid between the first end and the tapered region.

7 An advantage of the tapered region is that it can be used to increase the beam  
8 quality of the laser output while retaining the first end having a relatively large  
9 surface area – ideal for launching optical pump power having lower beam quality  
10 than the laser output.

11 The apparatus is particularly useful for increasing the brightness of the pump  
12 radiation via absorption into the rare earth dopant and wavelength conversion into  
13 modes guided by the core.

14 The pump radiation may be coupled from the pump source into the brightness  
15 converter using a coupling means. The coupling means may be a lens such for  
16 example as a cylindrical lens.

17 The apparatus may comprise a first reflector for reflecting optical radiation  
18 emerging from the first end. The apparatus may also comprise a second reflector.

19 The pump source may comprise at least one laser diode, laser diode bar, laser  
20 diode stack, or a laser diode mini-bar stack. Alternatively or additionally, the pump  
21 source may include a solid-state laser, a gas laser, an arc lamp, or a flash lamp.

22 The apparatus may comprise a plurality of the pump sources, and a combining  
23 means for combining the pump radiation emitted by the pump sources. The  
24 combining means may comprise a beam splitter, a reflector, a polarisation beam  
25 combiner, a beam shaper, a wavelength division multiplexer, or a plurality of optical  
26 fibres in optical contact along at least a portion of their length.

27 The brightness converter may have multiple cores, or a single core. The  
28 brightness converter may be circular or non-circular. The brightness converter may  
29 have a cross-section that is rectangular, is a regular or irregular shaped polygon, or  
30 is D-shaped.

31 The brightness converter may comprise rare-earth dopant. The rare-earth  
32 dopant may be disposed in the core and/or the first cladding. The rare earth dopant  
33 may be selected from the group comprising Ytterbium, Erbium, Neodymium,

1 Praseodymium, Thulium, Samarium, Holmium, Dysprosium, Erbium codoped with  
2 Ytterbium, or Neodymium codoped with Ytterbium.

3 The brightness converter may comprise a second cladding.

4 The apparatus may comprise a waveguide that is pumped by the brightness  
5 converter. The brightness converter may be doped with neodymium and/or  
6 ytterbium. The waveguide may be doped with ytterbium, erbium, or erbium co-  
7 doped with ytterbium.

8 The brightness converter may be defined by a width. The width may be in the  
9 range 0.1mm to 100mm. The width may be in the range 0.2mm to 25mm.  
10 Preferably the width is in the range 5mm to 15mm.

11 The brightness converter may be defined by a breadth. The breadth may be in  
12 the range 0.1mm to 100mm. The breadth may be in the range 0.2mm to 25mm.  
13 Preferably the breadth is in the range 2mm to 15mm.

14 The brightness converter may be defined by a length. The length may be in the  
15 range 1mm to 2000mm. The length may be in the range 10mm to 200mm.  
16 Preferably the length is in the range 10mm to 50mm.

17 The brightness converter can be formed from an optical fibre preform. The  
18 preform can be made from silica, silicic, phosphate or phosphatic glass. The preform  
19 may contain longitudinally extended holes. The preform may include stress rods.

20 The apparatus may be in the form of a laser, a Q-switched fibre laser, a master  
21 oscillator power amplifier, or a laser that contains a frequency converter.

### 23 **Brief Description of the Drawings**

24 Embodiments of the invention will now be described solely by way of example  
25 and with reference to the accompanying drawings in which:

26 Figure 1 shows apparatus for providing optical radiation according to the  
27 present invention;

28 Figure 2 shows apparatus comprising a plurality of pump sources;

29 Figures 3 to 5 show examples of brightness converters;

30 Figure 6 shows apparatus in which the brightness converter has been drawn  
31 down to a fibre;

32 Figure 7 shows apparatus comprising a waveguide;

33 Figure 8 shows apparatus comprising an intermediate fibre;

1 Figure 9 shows apparatus in the form of a Q-switched laser comprising a Q-  
2 switch;

3 Figure 10 shows a cross-section of the brightness converter of Figure 9;

4 Figure 11 shows apparatus in the form of a master oscillator power amplifier;

5 Figure 12 shows apparatus in the form of a master oscillator power amplifier,  
6 which utilizes the brightness converter to pump a waveguide;

7 Figure 13 shows apparatus in the form of a laser that comprises a frequency  
8 converter within the cavity;

9 Figure 14 shows apparatus in which a plurality of pump sources have been  
10 combined by a plurality of optical fibres in a common coating;

11 Figure 15 shows a cross section of the optical fibres in a common coating  
12 described with reference to Figure 14;

13 Figure 16 shows a preferred embodiment of the invention;

14 Figure 17 shows a cross-section of a beam converter in which the cores are  
15 arranged in a row;

16 Figure 18 shows a composite beam profile; and

17 Figure 19 shows the cross-section of an optical fibre intended for delivery to  
18 the point of use.

### 20 Detailed Description of Preferred Embodiments of the Invention

21 Referring to Figure 1, there is provided apparatus for providing optical radiation  
22 10, which apparatus comprises a pump source 1 for providing pump radiation 2, and  
23 a brightness converter 3, the apparatus being characterised in that the brightness  
24 converter 3 includes a substantially rigid region along at least a portion of its length.

25 An advantage in providing a brightness converter that is substantially rigid  
26 along at least a portion of its length is that good beam quality (a beam parameter  
27 product less than 12.5mm.mrad, combined with high power (greater than 500W, and  
28 preferably greater than 5kW) can be achieved in a solid state laser having relatively  
29 stiff member. It also provides a route to achieving beam parameter products less  
30 than 8mm.mrad, and preferably less than 5mm.mrad.

31 The brightness converter 3 comprises a core 4, a first cladding 31, rare earth  
32 dopant 5, a first end 6, a second end 7, and a tapered region 8 located between the  
33 first end 6 and the second end 7, the apparatus being characterised in that the  
34 cross-sectional area of the first end 6 is greater than the cross-sectional area of the

1 second end 7, and the brightness converter 3 is substantially rigid between the first  
2 end 6 and the tapered region 8.

3 Preferably, the tapered region 8 should be sufficiently long that optical radiation  
4 10 does not suffer loss as it propagates along the tapered region 8. In other words,  
5 it is preferably that the tapered region 8 is an adiabatic taper. The brightness  
6 converter 3 can be defined by a numerical aperture 18 between the core 4 and the  
7 first cladding 31. The angle subtended by the tapered region 8 at the interfaced  
8 between the core 4 and the first cladding 31 should be less than the numerical  
9 aperture 18. Thus if the numerical aperture 18 is 0.1, the angle 19 subtended by the  
10 tapered region 8 should be less than 0.1rad (or 100mrad). Preferably the angle 19  
11 should be between two to ten times smaller than the numerical aperture 18. An  
12 advantage of an adiabatic taper is that the brightness converter 3 will have all the  
13 advantages provided by a relatively large cross-sectional area (greater than  $2\text{mm}^2$ ,  
14 or preferably greater than  $10\text{mm}^2$ ) of its first end 6 which facilitates launching of  
15 pump radiation 2, while providing a mechanism for achieving higher beam quality by  
16 for example arranging feedback of the optical radiation 10 from the second end 7 in  
17 order to form a laser cavity.

18 The apparatus is particularly useful for increasing the brightness of the pump  
19 radiation 2 via absorption into the rare earth dopant 5 and wavelength conversion  
20 into modes guided by the core 4. The apparatus can be such that the optical  
21 radiation 10 has a higher brightness than the pump radiation 4.

22 The pump radiation 2 is coupled from the pump source 1 into the brightness  
23 converter 3 using a coupling means 9. The coupling means 9 may be a lens such as  
24 a cylindrical lens.

25 The apparatus comprises a first reflector 11 to reflect optical radiation 10  
26 emerging from the first end 6. The apparatus also comprises a second reflector 12.  
27 The second reflector 12 is configured to reflect optical radiation 10 emerging from  
28 the second end 7. The first and second reflectors 11, 12 form a laser cavity 13.  
29 Preferably, the reflectivity of the first reflector 11 is greater than the reflectivity of the  
30 second reflector 12 at the wavelength of the optical radiation 10. The first reflector  
31 11 can be a mirror, a dichroic mirror, a dielectric mirror, a reflector or a grating. The  
32 second reflector 12 can be a mirror, a dichroic mirror, a dielectric mirror, a reflector, a  
33 grating, or a Bragg grating such as a fibre Bragg grating. The second reflector 12



1 can alternatively be formed by the few percent reflection from a dielectric (such as  
2 glass) and air interface.

3 The pump source 1 can be a laser diode, a laser diode bar, a laser diode stack,  
4 or a laser diode mini-bar stack. A laser diode stack is a stack of diode bars with  
5 each bar typically containing ten to nineteen laser diode stripes (or even more),  
6 whilst a mini bar stack would typically contain a stack of diode-bars with each diode  
7 bar containing two to nine laser diode stripes. A laser diode mini-bar stack is  
8 especially useful because it allows pump light to be coupled into optical fibres having  
9 diameters in the range 100 $\mu$ m to 5000 $\mu$ m, with the advantage that beam shapers  
10 can be avoided. Arranging mini-bars into stacks and coupling the pump radiation  
11 into optical fibres is new and provides important economic advantages over the prior  
12 art. Alternatively or additionally, the pump source 1 can be a solid-state laser, a gas  
13 laser, an arc lamp, or a flash lamp.

14 Figure 2 shows apparatus in the form of a laser 20. The laser 20 comprises  
15 three pump sources 1, a combining means 21 and a coupling means 22. The  
16 coupling means 22 may be a lens such as a cylindrical lens. The combining means  
17 21 can be a beam splitter.

18 The combining means 21 may contain reflectors to combine the pump radiation  
19 2 from a plurality of pump sources 1. The combining means 21 may be a beam  
20 splitter. The pump sources 1 may be laser diode stacks. The reflector may be a  
21 striped reflector for interleaving the pump radiation 2 from the laser diode stacks.

22 The combining means 21 can be or can include a polarisation beam combiner,  
23 which is advantageous for polarisation multiplexing.

24 The combining means 21 and/or the coupling means 22 can also include one or  
25 more beam shapers such as are described in United States patent Nos. 5243619,  
26 5557475, 5825551, 6005717, 6151168, 6229940, 6240116, RE 33722, which  
27 patents are hereby incorporated herein.

28 The combining means 21 can be or can include a wavelength division  
29 multiplexer configured to combine the pump radiation 2 from two pump sources 1  
30 having different wavelengths.

31 Beam combining, interleaving, polarisation multiplexing, and wavelength  
32 division multiplexing can be used to couple the pump radiation 2 from two to four, or  
33 more, pump sources 1 into the brightness converter 3.

1        Figures 3, 4 and 5 show examples of the cross-sections at the first end 6 of the  
2 brightness converter 3. The brightness converter 3 can have multiple cores 4, or a  
3 single core 4. Although the brightness converter 3 can be circular, a non-circular  
4 cross-section can provide greater coupling between cladding modes and modes  
5 guided in the cores 4 as is described more fully in United States patent No. 4815079  
6 which is hereby incorporated by reference herein. The brightness converter 3 can  
7 have a cross-section that is rectangular, is a regular or irregular shaped polygon, or  
8 is D-shaped. The refractive index of the core 4 is preferably greater than the  
9 refractive index of the first cladding 31. The rare-earth dopant 5 can be disposed in  
10 the core 4 and/or the first cladding 31. The rare earth doping 5 may be selected  
11 from the group comprising Ytterbium, Erbium, Neodymium, Praseodymium, Thulium,  
12 Samarium, Holmium, Dysprosium, Erbium codoped with Ytterbium, or Neodymium  
13 codoped with Ytterbium. The brightness converter 3 may include a second cladding  
14 51 as shown with reference to Figure 5. The refractive index of the second cladding  
15 51 is preferably lower than the refractive index of the first cladding 31. The second  
16 cladding 51 may be a polymer. Alternatively the second cladding 31 can be a glass  
17 such as fluorine doped silica.

18        Referring to Figure 3, it may be advantageous to dope the cores 4 on the  
19 periphery of the beam converter 3 with a higher concentration of the rare earth  
20 dopant 5 in order to absorb the higher-order cladding modes (guided by the first  
21 cladding 31) more heavily than the lower order cladding modes. This is because the  
22 higher-order cladding modes will leak more preferentially in the tapered region of  
23 Figure 1.

24        Figure 6 shows apparatus in the form of a laser 60 in which the brightness  
25 converter 3 is drawn down to a fibre 61. The second reflector 12 is configured as a  
26 fibre Bragg grating 62 written in at least one of the core 4 or first cladding 31. An  
27 end cap 63 is shown in order to expand the optical radiation 10 prior to it leaving the  
28 fibre 61. This is advantageous to reduce the probability of damage at the fibre / air  
29 interface. The end cap 63 may be fused silica, which is preferably polished for  
30 example by laser polishing. The end cap 63 may be fused (eg by laser fusing) to the  
31 fibre 61. The end cap 63 may be antireflection coated.

32        A heat sink 66 is also shown for removal of heat from the brightness  
33 converter 3. The heat sink 66 can be air cooled or water cooled. Preferably the heat  
34 sink 66 is configured to provide two dimensional contact with the surface of the

1 brightness converter 3. This can be achieved if the brightness converter 3 contains  
2 at least one flat surface as would be provided for example by the cross-sections  
3 shown in Figures 3 to 5. Alternatively or in addition, the brightness converter 3 may  
4 be cooled by surrounding it in fluid, which fluid is preferably flowing. The fluid may  
5 be a gas such as nitrogen or argon gas or may be a liquid such as water or oil, or a  
6 water glycol mixture suitable for operation in cold climates.

7 Figure 7 shows apparatus in the form of a laser 70 in which the laser 60 is used  
8 to pump a waveguide 71 that comprises at least one core 75, at least one cladding  
9 76, and a gain medium 77. The gain medium 77 can comprise at least one rare-  
10 earth dopant disposed in one or both of the core 75 and cladding 76. The laser 60  
11 can be replaced with the apparatus shown in Figure 1 or Figure 2. The waveguide  
12 71 can be core pumped or cladding-pumped. Core and cladding pumped fibre  
13 lasers are described further in United States patent Nos. 4815079, 6288835 and  
14 6445494, which are hereby incorporated herein by reference. The waveguide 71 is  
15 shown coupled to the laser 60 by a splice 72. Alternatively, lenses can be used to  
16 couple the laser 60 to the waveguide 71. The waveguide 71 is shown as having a  
17 first and second fibre Bragg grating 73, 74 in order to form a laser cavity 78.

18 Advantages of the double pumping scheme shown in Figure 7 includes better  
19 thermal distribution. Thus for example, if the gain medium 77 was based on erbium  
20 for operation at so-called eye-safe wavelengths ( $>1500\text{nm}$ ), then the laser 60 can be  
21 configured to emit optical radiation 10 in the wavelength range  $1470\text{nm}$  to  $1550\text{nm}$   
22 by selecting first and second reflectors 11, 62 to reflect at a desired wavelength in  
23 the wavelength range  $1470\text{nm}$  to  $1559\text{nm}$  in order to pump the gain medium 77.  
24 The laser 60 can in turn be pumped by laser diodes in the wavelength range  $910\text{nm}$   
25 to  $1060\text{nm}$  (if the rare earth dopant 5 is erbium codoped with ytterbium) or by laser  
26 diodes in the wavelength range  $974\text{nm}$  to  $976\text{nm}$  (if the rare earth dopant is erbium).  
27 More heat will be dissipated in the beam combiner 3 than the waveguide 71 because  
28 the difference between pump wavelength and emission wavelength would be greater  
29 in the beam combiner 3 than in the waveguide 71. The double pumping scheme  
30 thus provides a method to manage the thermal dissipation in fibre lasers.

31 Another advantage of the double pumping scheme shown in Figure 7 is that the  
32 brightness converter 3 provides a method of increasing the brightness of a pump  
33 source 1 for pumping the optical waveguide 71. This is particularly important if the  
34 waveguide 71 is single mode since it allows core pumping of the waveguide 71 from

1 a pump source 1 that has a lower brightness than the optical radiation 10. Similarly,  
2 a single mode or a multimode waveguide 71 that is cladding pumped can be made  
3 shorter if the pump radiation is higher brightness. This is because the length of a  
4 cladding pumped fibre laser that is required to achieve reasonable pump absorption  
5 (>50%) is dependant upon the ratio of the cross-sectional area of the waveguide 71  
6 to the cross-sectional area of its core 75 (or if a plurality of cores 75 are used, of the  
7 combined cross-sectional area of the cores 75). Advantages of shorter waveguides  
8 71 include increasing the threshold of non-linear effects such as stimulated Raman  
9 scattering and stimulated Brillouin scattering, particularly for high-power continuous  
10 wave and pulsed lasers for both materials processing and aerospace application.

11 Figure 8 shows apparatus in the form of a laser 80 that comprises an  
12 intermediate fibre 81 for transmission of the optical radiation 10 from the laser 60 to  
13 the waveguide 71. This is a particularly useful arrangement for use in materials  
14 processing applications (such as welding, drilling and cutting) because it allows  
15 separation of the pump source 1 from the waveguide 71 which can be located on, or  
16 in the vicinity of, a machine tool. Advantages include location of the pump source 1  
17 where the provision of services such as electrical power and chilled water are  
18 convenient, and the ability to use optical switches to share the pump source 1  
19 between several waveguides 71 which may be at different locations. Advantages  
20 also include a method to increase the susceptibility to undesirable non-linear effects  
21 such as stimulated Raman scattering and stimulate Brillouin scattering by  
22 transmitting relatively low brightness pump radiation over long distances (>10m to  
23 2km) to the waveguide 71 which then outputs higher brightness optical radiation 79.

24 Figure 9 shows apparatus in the form of a Q-switched laser 90 which comprises  
25 a plurality of laser diode modules 91 providing pump radiation 2 in optical fibre  
26 bundles 92. The pump radiation 2 from the fibre bundles 92 is imaged onto the  
27 brightness converter via the lenses 93, the dichroic mirror 94 and the Q-switch 95.  
28 The Q-switch 95 can be an acousto-optic modulator or an electro-optic modulator.  
29 The brightness converter 3 is formed from an optical fibre preform that has been  
30 necked down in to form the taper 8. The first end 6 preferably includes an anti-  
31 reflection coating. The second end 7 has a fibre Bragg grating 96 to reflect the laser  
32 radiation 10. The fibre bundles 92 can be replaced by individual fibres or lenses.

33 Figure 10 shows a cross-section 100 of the first end 6 of the brightness  
34 converter 3 with the pump radiation 2 from the fibre bundles 92 that have been

1 imaged onto its surface shown as individual spots having a diameter 105. The laser  
2 diode module 91 can be a FAP-B-60C-1200-BL Fiber Array Packaged Bar from  
3 Coherent, Inc. of the United States of America. The laser diode module 91 can  
4 provide 60W continuous wave power at 810nm with a beam diameter of 1.2mm with  
5 a numerical aperture of 0.16. Thus 780W of pump radiation can be imaged onto the  
6 brightness converter 3 without any magnification if for example the brightness  
7 converter has cross-sectional dimensions of width 101 of 10mm and breadth 102 of  
8 5mm. Increasing the magnification allows either a brightness converter 3 of lower  
9 cross-sectional area. Additionally or alternatively increasing the magnification would  
10 allow pump radiation from more laser diode modules 91 to be imaged. The numerical  
11 aperture of a brightness converter 3 made from silica and coated with a low index  
12 polymer can be 0.4. This would allow approximately 5kW of pump radiation to be  
13 launched onto the first end 6 of the brightness converter 3 using these relatively low  
14 brightness sources 91. Even higher powers can be achieved with soft glasses that  
15 have a higher refractive index.

16 If made using optical fibre preform technology, such a preform can be tapered  
17 down by a factor of around 100 (in linear dimensions) thus providing an output fibre  
18 having dimensions of 100 $\mu$ m by 50 $\mu$ m. Referring to Figure 9, with dopant  
19 concentrations of rare-earths (such as Neodymium) of a few mole %, and utilizing  
20 either large cores 4 or multiple cores 4 (see Figures 3 to 6), good absorption of the  
21 pump radiation 2 is possible in lengths 98 of untapered preform 99 of 1cm to 10cm,  
22 but preferably 2cm to 5cm. Higher launched power can be achieved by imaging the  
23 pump radiation 2 from more laser diode modules 91 onto the first end 7 in smaller  
24 spots (with higher numerical apertures).

25 With practical preform technologies, the width 101 can be in the range 0.1mm  
26 to 100mm, the breadth in the range 0.1mm to 100mm, and the length 98 in the range  
27 1mm to 2000mm. The technology lends itself to immediate application with the width  
28 101 in the range 0.2mm to 25mm, breadth 102 in the range 0.2mm to 25mm, and  
29 length 99 in the range 10mm to 200mm. Preferably, the width 101 will be in the  
30 range 5mm to 15mm, breadth 102 in the range 2mm to 15mm, and length 99 in the  
31 range 10mm to 50mm. The ratio of linear cross-sectional dimensions of the first end  
32 6 to the second end 7 can be in the range 2 to 1000, and preferably in the range 10  
33 to 250. By width 101 and breadth 102, it is meant two representative cross-sectional

1 measures across the cross-section 100. The cross-section 100 can be rectangular,  
2 circular, square, D-shaped, or other regular or irregular shape. The preform can be  
3 made from silica, silicic, phosphate or phosphatic glasses. The preform may contain  
4 longitudinally extended holes (not shown) along its length as are found in  
5 microstructured fibres, or stress rods such as are those used for inducing  
6 birefringence.

7 Figure 11 shows apparatus in the form of a master oscillator power amplifier  
8 (MOPA) 110 comprising a seed source 111 and a beam splitter 112. The beam  
9 splitter 112 is preferably dichroic. The seed source 111 may be a laser such as a  
10 fibre laser, a Q-switched laser, a pulsed laser, a femtosecond laser, or a  
11 semiconductor laser. The MOPA 110 is shown with the seed source 111 providing  
12 laser radiation 113 directed at the second end 7. This has the advantage that the  
13 brightness converter 3 will be less multi-moded at the second end 7 than the first  
14 end 6.

15 Figure 12 shows apparatus in the form of a master oscillator power amplifier  
16 (MOPA) 120, which utilizes the brightness converter 3 to pump the waveguide 71.  
17 The brightness converter 3 may be doped with neodymium and/or ytterbium such  
18 that low-brightness 810nm radiation is converted into laser radiation 10 having a  
19 higher brightness in a wavelength range that is absorbed by ytterbium (for example  
20 in the wavelength range 910nm to 1050nm, but preferably from 910nm to 920nm,  
21 975 to 980nm, or 1030nm to 1050nm). The waveguide 71 may be doped with  
22 ytterbium that is pumped by the laser radiation 10. Alternatively the waveguide 71  
23 may be doped with erbium as discussed further with reference to Figure 7. The  
24 arrangement shown in Figure 12 is advantageous for core-pumping the waveguide  
25 71 because it allows higher output powers to be achieved before reaching non-linear  
26 effects. An intermediate fibre 81 (not shown) can also be used to enable the pump  
27 source 1 to be located remotely from the waveguide 71 as discussed with reference  
28 to Figure 8.

29 Figure 13 shows apparatus in the form of a laser 130 that comprises a  
30 frequency converter 131 within the cavity 133 formed by the first reflector 11 and the  
31 second reflector 12. The frequency converter 131 may be a frequency doubler, a  
32 frequency tripler or a frequency quadrupler. The brightness converter 3 may be  
33 doped with neodymium and/or ytterbium. The first and second reflectors 11, 12 may  
34 be such that they reflect at the fundamental wavelength of the laser 130 (typically

1 from 910nm to 1100nm).The frequency converter 131 may utilize a crystal such as  
2 barium titanate or lithium niobate for the frequency conversion.

3 Figure 14 shows a plurality of minibar stacks 141 each of which are coupled  
4 into optical fibres 3, 142 using lens 143. The lens 143 may comprise a combination  
5 of a cylindrical and spherical lens configured to equalise the far field divergence  
6 angle of the pump radiation 2 in orthogonal directions and to couple it efficiently into  
7 the optical fibres 142. The optical fibres 3, 142 have a common coating 140 and are  
8 in optical contact along at least a portion of their length – see Figure 15 – such that  
9 pump power launched in optical fibres 142 couple into and pump the brightness  
10 converter 3. The optical fibres 142 can be tapered or untapered. The optical fibres  
11 3, 142 and can have circular, non-circular, square, or rectangular cross-sections.  
12 Non-circular cross sections assist in reducing the length over which the pump  
13 radiation is absorbed in the optical fibre 3. Increasing the optical contact between  
14 the optical fibres 3 and 142 by use of flat surfaces increase optical coupling between  
15 the fibres 3, 142.The examples provided in Figures 9 to 15 are based on fibre  
16 coupled laser modules 92. The brightness converters 3 described in these examples  
17 are also suited for simple coupling to either laser diode bars, laser diode stacks, or  
18 laser diode mini-bar stacks. These can be combined together or used separately,  
19 and can be continuous wave or pulsed. Examples are continuous wave laser diode  
20 stacks and bars with output powers of 10W to 1kW or more, and laser diode stacks  
21 that can instantaneous pulsed powers in excess of 1kW or more. The laser diode  
22 stacks or bars can be water cooled and/or air cooled. Minibar stacks may comprise  
23 up to 9 diodes per bar and up to 12 bars in a stack. These may supply as much as  
24 200W pump radiation or more.

25 Figures 16 to 19 show a preferred embodiment of the invention. The beam  
26 combiner 3 has a substantially rectangular cross-section as shown in Figure 17, and  
27 comprises a plurality of cores 4 arranged in at least one row. The cores 4, first and  
28 second claddings 31, 51 are formed from glass with the refractive index of the core 4  
29 being higher than the refractive index of the first cladding 31 which is higher than the  
30 refractive index of the second cladding 51. The first cladding 31 may be formed from  
31 pure silica, and the second cladding 51 be formed from fluorosilicate glass.

32 With reference to Figure 16, the beam combiner 3 is shown as having the first  
33 and second reflectors 11, 12 which may be fibre Bragg gratings that are formed in  
34 the cores 4. An advantage of having the cores 4 in a row is that it facilitates the

1 writing of fibre Bragg gratings using ultra violet light. This is because the cores 4 can  
2 be located at the same focal length from a phase mask in a fibre Bragg grating  
3 writing apparatus such as described in United States patent no. 6,072,926. The  
4 cores 4 preferably have a photosensitive region 171 (shown in Figure 17) such that  
5 fibre Bragg gratings can be written in them to form the first and second reflectors 11,  
6 12 (shown as a reflectors in Figure 16). The cores 4 may be formed in two rows,  
7 with the second row being formed by turning the beam combiner 3 around.

8 Figure 16 also shows a plurality of pump sources 1 that are arranged to launch  
9 pump radiation 2 into the first cladding 31. Preferably the pump sources 1 comprise  
10 a plurality of diodes stacks, diode mini-stacks, diode bars or single emitters that are  
11 arranged geometrically or with beam combiners to couple the pump energy into the  
12 first cladding 31. Diode stacks and bars typically emit a highly rectangular output  
13 beam. Such a rectangular output beam can be readily coupled to the rectangular  
14 beam converter 3 shown in Figure 17 without incurring the losses incurred by beam  
15 shapers incurred in launching pump radiation 2 from diode stacks into conventional  
16 optical fibres.

17 Optionally, the brightness converter 3 can be cooled by fluid 163 as shown in  
18 Figure 16. The fluid is pumped into an enclosure 161 via an input port 164 from a  
19 fluid source 165 such as a pump, and the fluid 163 exits via an exit port 166. Seals  
20 162 are provided between the enclosure 161 and the beam converter 3. The seals  
21 162 may comprise O-rings. The fluid 163 may be a gas such as nitrogen or argon.  
22 The fluid 163 may alternatively be a fluid comprising water, oil, glycol, or a mixture of  
23 water and glycol. Fluid cooling is a highly effective way of removing heat from a high  
24 power laser and is facilitated by the rigidity of the beam converter 3, the absence of a  
25 polymer coating, and by the presence of the second cladding 51. Such fluid cooling  
26 would be difficult to implement in a fibre laser having a flexible fibre because of  
27 reliability concerns involved in removing a relatively thin fibre's polymer coating and  
28 surrounding the fibre in fluid.

29 An optional lens array 167 provides collimation of the output radiation 10. In  
30 order to provide optimal beam quality, the lens array 167 should be positioned so  
31 that the diffracting laser radiation 10 from each of the cores 4 just meets. Thus  
32 allowing a beam shaper 168 to combine the individual beams 10 in order to provide  
33 a composite output beam 169. If there are seven cores 4, then the composite output  
34 beam 169 will have the beam profile 180 shown in Figure 18. Such a beam 169 will



1 have three times the beam parameter product of the output beam 10 from one of the  
2 cores 4. If the collimation provided by the lens array 167 and beam shaper 168  
3 leaves gaps between the individual beams 10, then the beam quality of the  
4 composite output beam 169 will be degraded. The composite beam 169 can be  
5 launched into an optical fibre 190 for delivery to the point of use (not shown). The  
6 optical fibre 190 is preferably designed to be a step index fibre having a core 191  
7 having the same or higher numerical aperture as the cores 4. If the central beam  
8 182 in Figure 8 is not present, then the optical fibre 190 can have a central region  
9 192 having the same or lower refractive index as the cladding 193. The optical  
10 output from such a ring-doped fibre would have a doughnut optical power  
11 distribution, and thus would be advantageous for cutting applications because it  
12 would have similar cutting power as an equivalent (ie same localised optical  
13 intensity) but higher total-power optical output having a top hat near-field distribution.

14 If seven cores 4 are used such as shown in Figure 17, then the composite  
15 beam 169 would have a beam parameter product approximately three times greater  
16 than the beam parameter product of the cores 4. Thus if the wavelength of the  
17 optical radiation is in the range  $1\mu\text{m}$  to  $1.1\mu\text{m}$ , and the cores 4 are single moded,  
18 then the beam parameter product of the composite beam 169 would be  
19 approximately 1 mm.mrad. Additional cores 4 can thus be used to provide a high  
20 power laser having a beam parameter product in the range 3 mm.mrad to 25  
21 mm.mrad. Alternatively or additionally, the cores 4 can be multimoded.

22 With referenced to Figure 17, the beam converter 3 can have a width 171  
23 between 2mm and 20mm, and a height 172 between 0.1mm and 5mm. The length  
24 175 (shown in Figure 16) of the beam converter 3 should preferably be such that the  
25 pump radiation 2 is absorbed. Suitable lengths 175 may be between 5mm and  
26 1000mm, and preferably 10mm to 20mm. Note that the higher the ratio of the  
27 combined areas of the cores 4 to the cross-sectional area of the first cladding 31 the  
28 shorter the beam converter 3 can be. The beam converter 3 shown in Figure 17 can  
29 be made by drawing down a rare-earth doped optical fibre preform into rods and  
30 inserting the rods into a silica substrate tube that has been drilled to accept the rods  
31 to form a composite preform. The composite preform can then be drawn on a fibre  
32 drawing tower.

1       The preferred embodiment shown in Figures 16 to 18 can be used with any of  
2 the configurations shown in Figures 1, 2, 6, 7, and 8. Thus for example, the  
3 apparatus of Figure 16 can have a beam converter 3 that is tapered, can form part of  
4 a master oscillator power amplifier, and can have intermediate pump delivery  
5 fibres 92.

6       It is to be appreciated that the embodiments of the invention described above  
7 with reference to the accompanying drawings have been given by way of example  
8 only and that modifications and additional components may be provided to enhance  
9 performance. In addition, the invention can be considered to be a laser, a Q-  
10 switched fibre laser, a master oscillator power amplifier, or a laser that contains a  
11 frequency converter.

12       The present invention extends to the above-mentioned features taken in  
13 isolation or in any combination.